Supporting Information

Facile Fabrication of Highly Conductive, Ultrasmooth, and Flexible Silver Nanowire Electrode for Organic Optoelectronic Devices

Dang-Thuan Nguyen and Hongseok Youn[*]

Department of Mechanical Engineering, Hanbat National University, Daejeon 34158, Korea.
*E-mail: hsyoun@hanbat.ac.kr

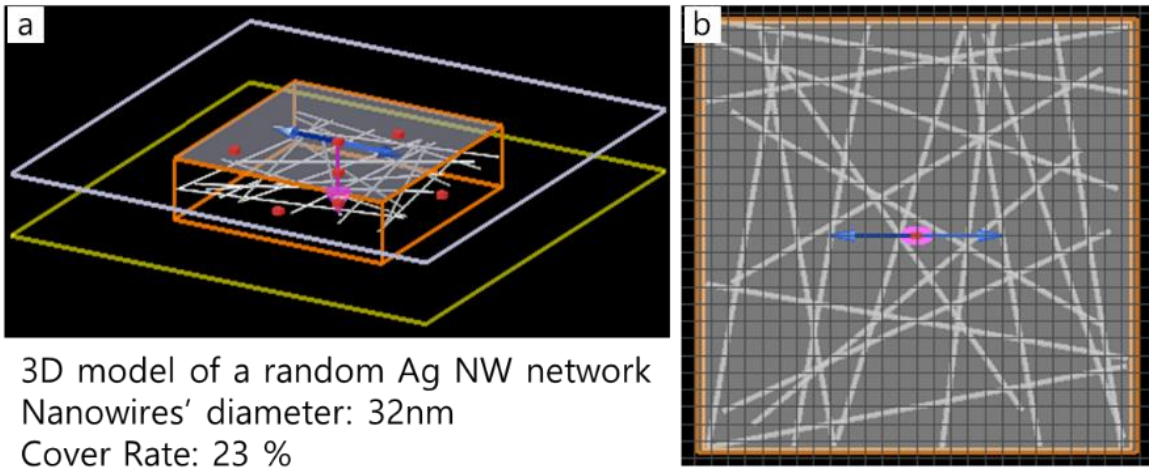


Figure S1. Simulation model of the random Ag NW network. Material's optical properties are used from materials data base (Johnson & Christy). (a) White rectangle represents light source (Gauss beam) while the yellow rectangle illustrates the monitor where the incident light is measured after transferring through the Ag NW network. (b) Top view of the Ag NW random network which provides a same cover rate (on the glass substrate) with the real samples (Figure 1a). The simulation results are shown in Figure 1c-d (red lines).

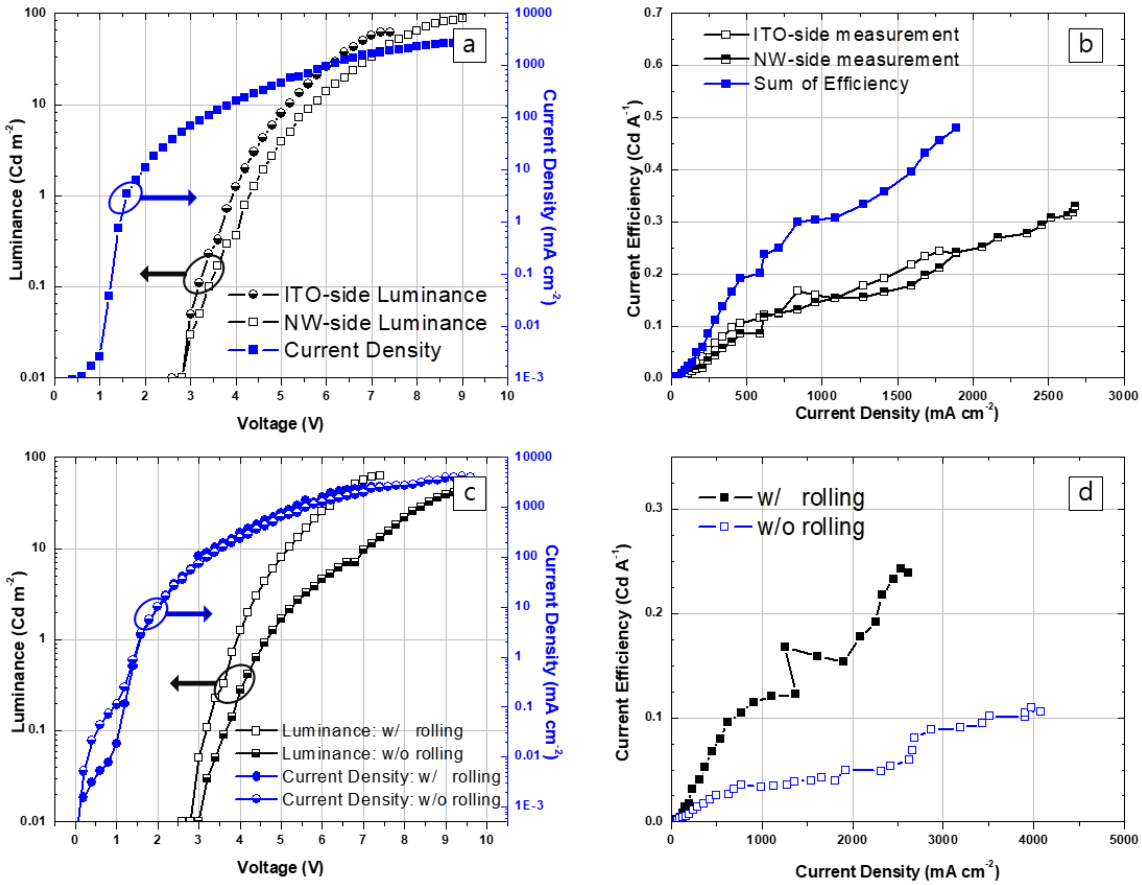


Figure S2. (a) Luminance and (b) Current Efficiency of a Transparent-OLED with measurements at two emission directions. (c) and (d) comparison of the efficiency of 2 electrodes (with and without rolling onto the surface of the SAM-treated glass) applied in the same T-OLED structure.

Figure S2a,b illustrates the efficiency of a Transparent-OLED with measurements at both emission directions. It's obvious that the luminance at the ITO side is quite higher than that of the nanowire-embedded film side in **Figure S2a** while both directions show a similar trend of Luminance at the same Current Densities and Applied Voltages. **Figure S2b** gives information about the Current Efficiency of the T-OLED, in which, the Current Efficiencies at two different directions are similar. Therefore, the sum of Efficiency is double of one direction. **Figure S2c,d** compares the efficiency of the samples using 2 electrodes (with and without post-transfer

treatment) applied in the same T-OLED structures. The decrease in the surface roughness is a huge advantage of the sample with an additional rolling step. **Figure S2c** shows that at low voltage, the current leakage in the non-rolling treatment sample is much higher than that of rolling treatment one. **Figure S2d** describes Current Efficiency, one more time, confirms the advantage of a planner surface with a higher efficiency.

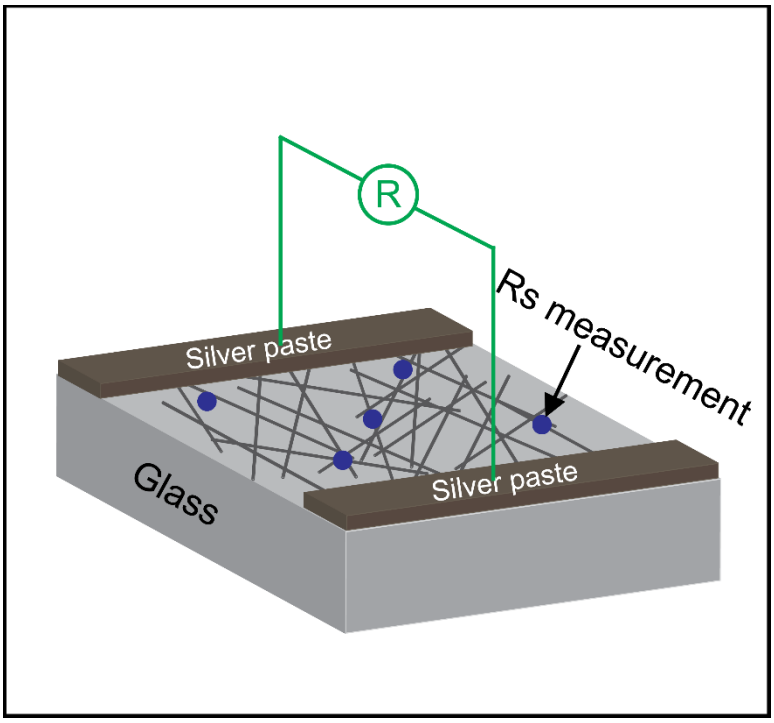


Figure S3. Silver paste is used as electrodes for the Joule heating and the sheet resistance calibration during the Joule heating.

The contacts between tips of the SourceMeter and the Ag NW network on the glass substrate are point-contact, thus, to have stable conditions during the Joule heating process, the silver paste is used to get area contacts that would results in a uniform crossing of current. The sheet resistance of the Ag NW network is a calibration from resistance measured from two silver paste electrodes. Firstly, we measured sheet resistance 5 times in 5 different areas in one sample and then took the average value. Secondly, we measured resistance between two silver paste

electrodes. Thus, we could calibrate the relationship between the average sheet resistance of one sample and its resistance.

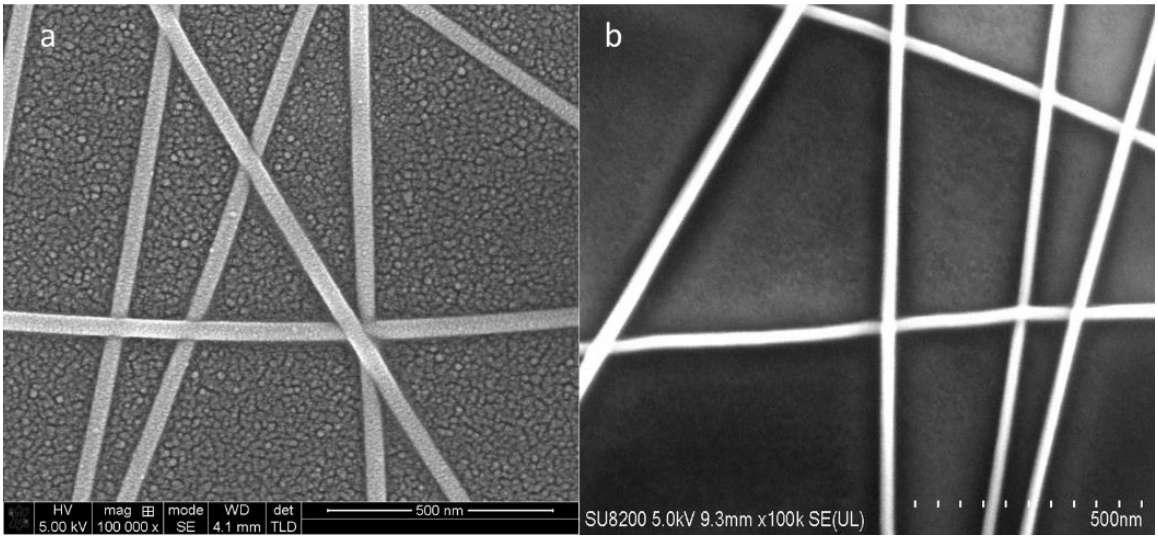


Figure S4. SEM images of samples including the Ag NW and the silver precursor mixing after the Joule heating with (a) and without (b) Platinum coating. These images show that there is no precursor or silver crystal/ particle on the glass substrate.

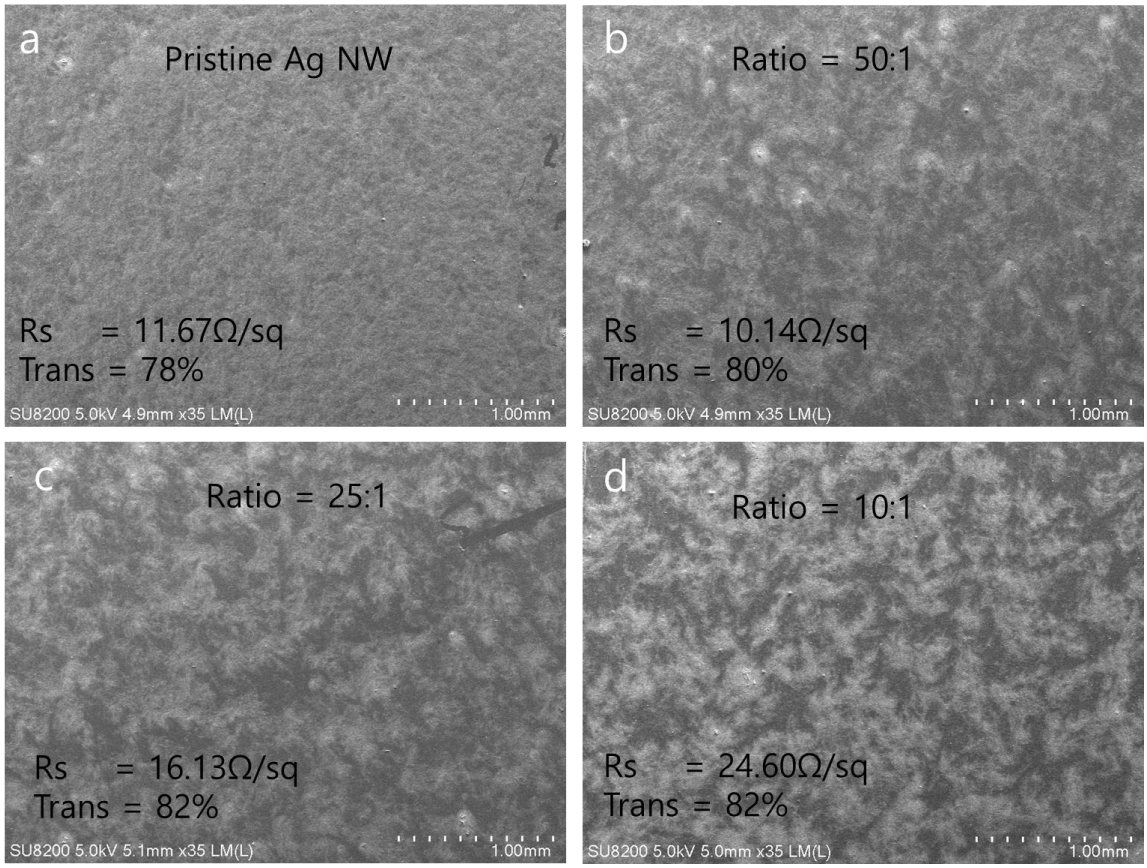


Figure S5. Coating quality comparison. SEM images of a pristine (a) Ag NW and mixing samples with ratio between Ag NW and Ag precursor ink was 50:1 (b), 25:1 (c), and 10:1 (d). The transmittance (Trans) and the sheet resistance (Rs) of the pristine Ag NW and mixing samples after the Joule heating (including the glass substrate). It's noticeable from the figures that the higher concentration of the silver precursor ink is, the lower coating qualities of the samples are. In order to have the highest coating quality and the most effective treatment of mixing and Joule heating, we chose the ratio between Ag NW and silver precursor ink was 50:1.

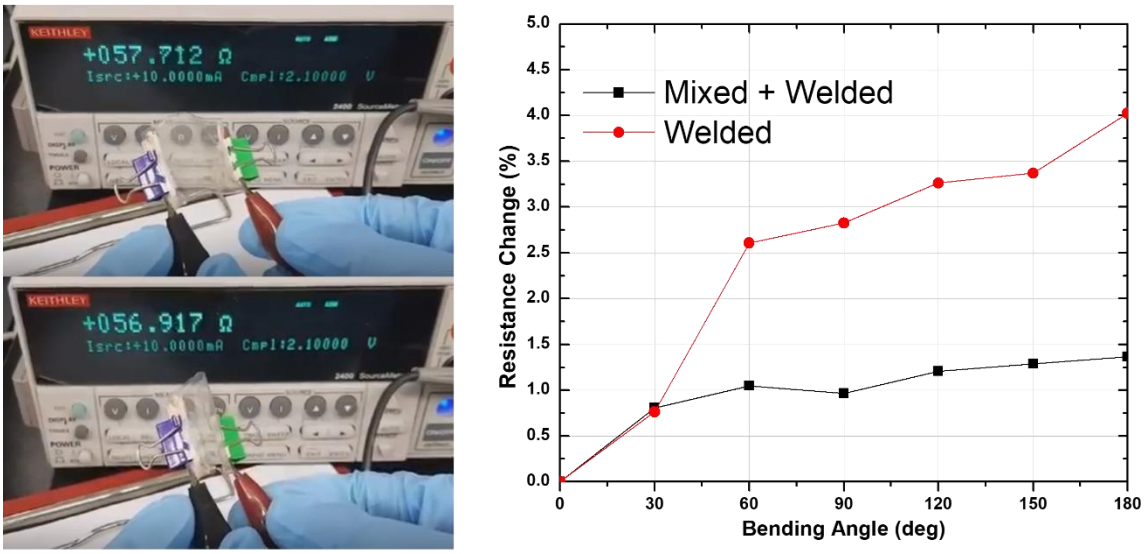


Figure S6. Bending test comparison between the pristine welded nanowires embedded in the polyamide film and the nanowires treated with the silver precursor after the Joule heating and embedding in the polyamide film.

For better understanding, the resistance was measured between 2 silver paste electrodes as can be seen in the sub-image in the left of Figure. It is clear that the amount of adding materials show their contributions to the stability of the nanowire network when the film was bent.

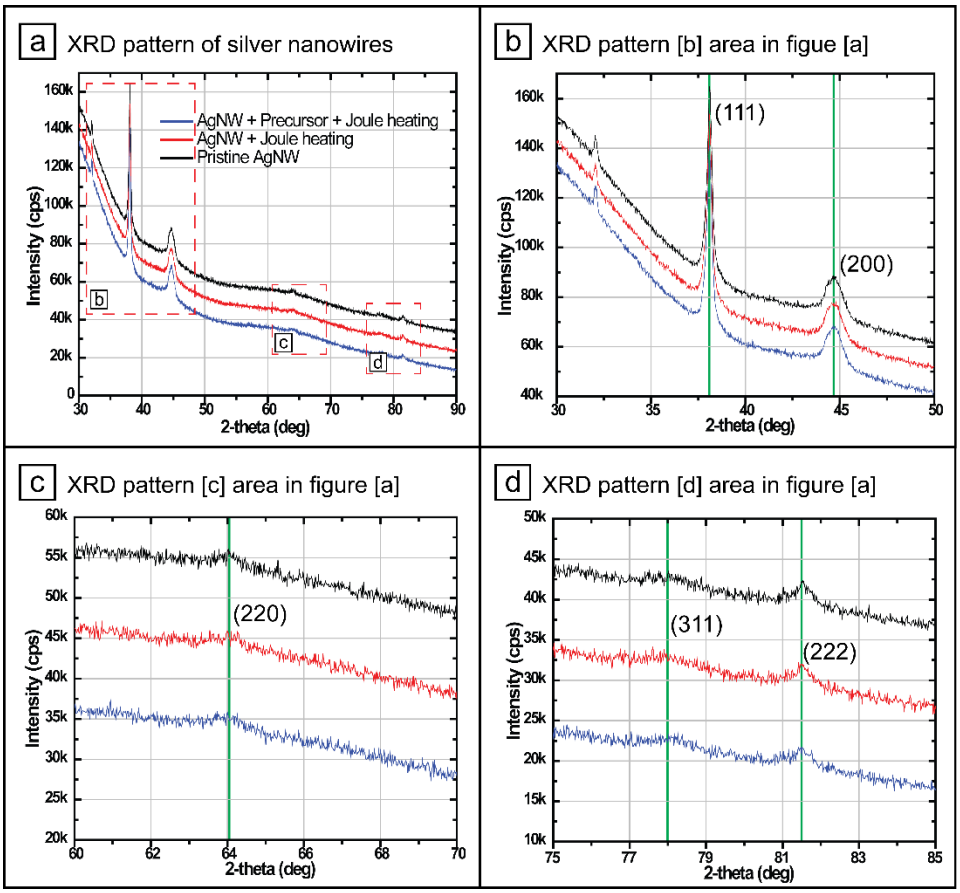


Figure S7. XRD analysis of the crystallinity of the Ag NW network. (a) Full range of XRD, (b-d) closer zoom in special areas.

Table S1. Comparison of results with references in terms of sheet resistance, transmittance, and roughness.

Ref.	Authors	Rq (nm)	Rs (Ω/□)	Trans. (%)	
				w/ substrate	w/o sububstrate
31	Zeng, X. Y. et al.	1.27	182	88	130um PVA
32	Yu, Z. et al.	<5	100	-	91
33	Gaynor, W. et al.	11.9	12	-	86
34	Gaynor, W. et al.	6~8	12.5	-	92
35	Nam, S. et al.	0.4	16	82.3	100um NOA 63
36	Huang, Q. et al.	<1	5.6	58.1	Pure PI sub.: 92.2%
37	Ricciardulli, A. G. et al.	4.6	13.7	80 (Not describe sub.)	
38	Lu, L. et al	4.2	10.1	87	2um PVB
39	Tang, H. et al	2.3	26	83.32	150um PUA
This work	Glass substrate	33.16	9.9	83	92
	Polyamide film	1.92	10.9	78 (50um PA)	92

It’s noticeable that our experiments were done with a low grade of polyamide film whose transmittance is quite lower than commercial grade (~90%).

In a direct comparison with a latest publication from H. Tang group (June 2019 at ACS Applied Materials & Interface), to have a TCE with 26 Ohm/sq sheet resistance at 83.32% transmittance (at 550nm) and 2.3nm roughness, the study requires a complex process: annealing Ag NW after coating on glass substrate, then coat PUA (solution) which requires UV treatment. The final step is MXene aqueous coating that also requires annealing. It is clear that our processes are simpler and less time-consuming without any special equipment such as UV.

Table S2. SEM - EDS analysis results

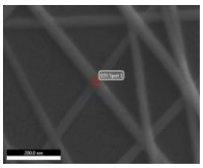
Sample	Weight %			Atomic %			
	C	N	Ag	C	N	Ag	
Mixed (w/o Joule heating)	14.25	**19.64**	19.98	24.82	**29.34**	3.88	
Mixed + Joule heating	9.44	**0.02**	30.21	24.35	**0.05**	8.67	
Ag NW	8.37	**0.02**	26.62	20.57	**0.05**	7.29	

Table S2 clearly illustrates the difference in the percentage of chemical elements of 2 samples before and after applying the Joule heating and reference is one sample of the Ag NW without mixing the silver precursor ink. Before having a look at figures for each element in the table, we must notice that the purchased Ag NW solution contains residual polymer from the Ag NW synthesis process. That is the reason why in all samples, the proportion of carbon is significant. Paying attention to the nitrogen element which only exists in the silver precursor ink, it is clear that the ratio of the nitrogen in the sample before applying the Joule heating is relatively high,

and then, after treatment, this percentage decreased to less than 0.1% and could be neglected. Therefore, we believe that the silver precursor is totally reduced to silver after the Joule heating process.

Table S3. Sheet resistance of Ag NW samples with a same absolute transmittance of 92% at 550nm before and after treatments.

Sample Number	Befor Joule heating/ Glass substrate	After Joule heating/ Glass substrate	After transferring/ Embedded film
1	15.44 Ohm/sq	13.13 Ohm/sq	13.56 Ohm/sq
2	16.11 Ohm/sq	12.80 Ohm/sq	15.29 Ohm/sq
3	16.12 Ohm/sq	13.88 Ohm/sq	16.05 Ohm/sq
4	17.60 Ohm/sq	14.09 Ohm/sq	14.15 Ohm/sq
5	16.79 Ohm/sq	13.53 Ohm/sq	15.58 Ohm/sq
Average	16.41 Ohm/sq	13.49 Ohm/sq	14.93 Ohm/sq

***/ Note:** the Table S3 was added in the revision, therefore the average sheet resistance was different from the main text because of the difference in the samples. Additionally, the sheet resistance for each sample was an average value of 5 measurements in 5 areas in one sample to avoid the random arrangement effect of the nanowires. In sample 4, the best result of the sheet resistance was 10.9 Ohm/sq on the polyamide film.

Table S3 gives information about the sheet resistance of the Ag NW network at the same absolute transmittance of 92% (at 550nm). While the total transmittance (including the substrate) of these samples in the glass substrate was 83%, after transferring to the Polyamide film, the total transmittance dropped to 78%. It could be explained by the transmittance of the bare substrate, the transmittance of pure glass is 91% whereas the transmittance of the polyamide 50um is 84%.

It’s noticeable that our experiments were done with a low grade of polyamide film whose transmittance is quite lower than commercial grade (~90%).

Tabls S4. Comparison of Current efficiency and Luminance with references of PLEDs.

R.	Authors	Electrodes materials	Emitting material	Current eff. (cd/A)	
				Bottom	Top
1	Kee, S. et al	Polymer	SuperYellow	1.5	1.3
1	Kee, S. et at	Polymer	SPW-111 (Merck)	1.7	1
2	Liang, J. et al	Ag NW	SuperYellow, ETPTA, PEO, LiTf in THF (ratio 20:2:2:1)	5.6	-
3	Liang, J. et al	Ag NW + GO	a white-light-emitting polymer: OXD-7 (100:10)	2	2
4	Chung, J. et al	ITO & LiF/Al/Ag	CBP:Ir(ppy)3	EQE total 15%	
5	Zang, Y.-B. et al	ITO & (NPB/ MoO3/ Al-Ag-Ca:Ag/ MoO3)	TAPC/Flrpic:mCP/PO-01:mCP/TmPyPD/ Cs2Co3:Alq3	Total: 109.1	
This work		ITO & Ag NW	SupperYellow	1.61	1.6